

Improvements of the Semidynamic Method for Capillary Pressure Measurements

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Abstract

The semidynamic method provides the entire water-oil capillary pressure cycle (drainage and imbibition for both positive and negative P_c) for any type of wettability. It is based on the steady-state injection of one fluid through the sample. To simplify the method, the measurement of the local saturation has been replaced by its calculation from the average saturation, as in the centrifuge method. In order to check the validity and accuracy of this calculation, several experiments were performed with both measurement (CAT scanner) and calculation of the local saturations. We used the analytical calculation of the local saturation proposed by Ramakrishnan and Cappiello (1991). Calculated saturations agree with scanner measurements for intermediate values, but there is no accuracy for the S_{wi} value. The reason is that the calculation is based on the derivative curve of the pressure vs. flow rate. Results of the analytical method were then used as a first guess for numerical simulations of the displacement. The final P_c and K_r curves were then determined by fitting the simulated average saturation and local pressures with the experimental values. The whole range of saturations, and especially S_{wi} was then accurately determined within the accuracy of saturation measurement from CAT scanning (± 2 saturation units).

Introduction

Capillary pressure curves are generally obtained by porous plate or centrifuge methods. Both methods have their drawbacks, especially for imbibition curves and mixed wettability samples. An original method called semidynamic was proposed at the 1993 SCA conference (Lenormand *et al.*, 1993). This paper describes an improvement of this method.

Let us first review the principle of the method based on the equilibrium between the capillary pressure and the viscous pressure drop. The experimental set-up is described in Figure 1. It consists of a standard core-holder (epoxy coating or Hassler cell) without any semipermeable membrane and a separator used to measure the fluid production. The saturations are measured at different sections of the sample by using an ultrasonic method. Any other technique could be used (conductivity, X-ray, γ -ray, etc.).

Oil is injected through the sample and water only "washes" the outlet face of the sample (Fig. 1) in order to establish the continuity between water inside the sample and the outlet. The continuity of the water phase enable the measurement of the water pressure in the outlet: when the steady state is reached, water is no longer produced, and therefore, there is no pressure gradient in the water phase. The water pressure P_w is uniform along the sample, but there is a gradient in the oil that is flowing. The second role of the

washing of the outlet is to enable the invasion of water into the sample during imbibition when the pressure in oil is decreased.

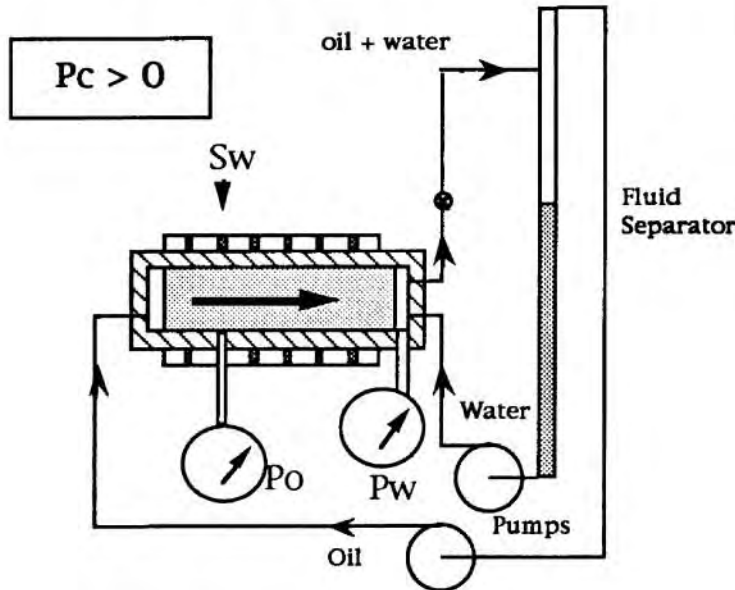


Fig. 1. Principle of the experimental set-up.

The pressure P_o in the oil is measured through a hole in the coating or the rubber sleeve of the core-holder. Through this hole, the pressure is measured in the fluid that would flow through the opening (i. e. the injected fluid). This property can easily be proved. Let us assume that both fluids 1 and 2 are present in the "hole" in connection with the porous medium (Fig. 2). The size of the cavity is large compared to the pore size and the interface between the fluids is flat in the cavity (there is no capillary pressure). Inside the medium, we assume

that the pressure is greater in fluid 2. If the fluids are both connected to the cavity, the pressure is greater in fluid 2. Consequently, since there is no capillary pressure, fluid 2 pushes fluid 1 until it occupies the whole cavity. When equilibrium is reached, the pressure in the "hole" is equal to the pressure in fluid 2 in the porous medium, pressure which is measured.

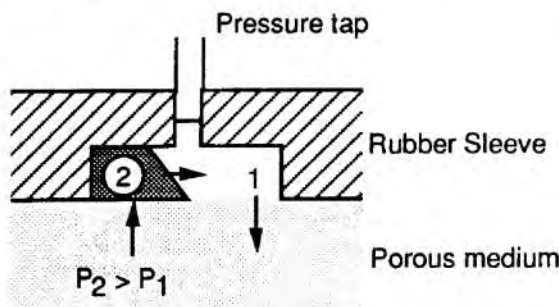


Fig. 2. Principle of the pressure measurement. The hole in the rubber sleeve is filled with fluid 2 when $P_2 > P_1$ inside the porous medium.

For positive P_c , the pressure measured is the oil pressure. For negative P_c , when water is injected, the pressure is the water pressure. From the values of P_w and P_o , we can calculate the capillary pressure defined as $P_c = P_o - P_w$.

The method also requires the measurement of the saturation S_w at the same location to obtain one $P_c(S_w)$ point of the capillary pressure curve. The primary drainage curve is obtained by increasing the oil flow rate from zero in a sample initially saturated with water. Imbibition is obtained by decreasing the oil flow rate. During all these displacements, the water flow rate is kept constant at a low value to prevent any disturbance of the flow in the sample (negligible pressure drop) but high enough to wash out the oil in the outlet.

The negative part of the Pc curve is obtained by permuting the roles of oil and water. Negative imbibition is obtained by increasing the water flow rate, and secondary negative drainage by decreasing this flow rate. Secondary positive drainage is obtained by injecting oil again.

However, this first version of the method had the drawback of needing the measurement of saturation at a few points along the sample. For this purpose, we used an ultrasonic technique, which is accurate but impossible to use with gas and difficult to incorporate in an automatic set-up. The problem has been solved by calculating the saturation from the average saturation. This new approach is based on a very smart analytical calculation proposed by Ramakrishnan and Capiello (1991) and based only on the measurement of the entrance pressure (and average saturation). However, we have shown that the calculation based only on the entrance pressure is not accurate enough and that local pressure measurements and additional numerical treatment are required. This approach may be an improvement because pressure is much easier to measure than saturation. In addition, pressure is less sensitive to local core sample heterogeneities than saturation. On the other hand, there are the problems of accuracy, especially for Swi, and the complexity of the inversion calculation. This paper is a first analysis of this new approach.

Analytical calculation of the local saturation

The calculation proposed by Ramakrishnan and Capiello in 1991 corresponds to the flow conditions of the semidynamic method.

Darcy's law is written below for two immiscible phases (fluids 1 and 2) flowing in direction x:

$$q_1 = -K \frac{K_{r1}}{\mu_1} A \frac{\partial P_1}{\partial x} \quad q_2 = -K \frac{K_{r2}}{\mu_2} A \frac{\partial P_2}{\partial x} \quad (1),(2)$$

q is the volume flow rate, P the pressure, K and Kr are the single-phase and relative permeabilities; μ the viscosity and A the cross section area of the sample. When the steady-state is reached, only fluid 2 (oil, for $P_c > 0$) is flowing at a uniform flow rate q_2 and water is no longer produced ($q_1 = 0$). The pressure P_1 in water is then uniform and will be taken as a reference ($P_1 = 0$). The relative permeability K_{r2} can be written as a function of the capillary pressure $P_c = P_2 - P_1$. Equation 2 is rewritten as:

$$q_2 dx = -K \frac{K_{r2}(P_c)}{\mu_2} A dP_c \quad (3)$$

and then integrated between the entrance ($x=0$), where $P_c = P_e$ and outlet ($x=L$), with $P_c(L)$:

$$q_2 L = K \frac{A}{\mu_2} \int_{P_c(L)}^{P_e} K_{r2}(P_c) dP_c \quad (4)$$

The originality of Ramakrishnan's calculation is to consider the series of experiments performed at different flow rates. The entrance pressure P_e is then a function of the flow rate q_2 . The capillary pressure $P_c(L)$ at the outlet remains constant and equal to zero as in centrifuge experiments (O'Meara *et al.*, 1988). Equation 4 is then differentiated with respect to P_e :

$$\frac{dq_2}{dP_e} = \frac{KA}{L\mu_2} K_{r_2}(P_e) \quad (5)$$

This equation gives the relative permeability of the injected fluid as a function of the derivative of the entrance pressure:

$$K_{r_2} = \frac{L\mu_2}{KA} \frac{dP_e}{dq_2} \quad (6)$$

The local water saturation S can be derived from the average saturation $\langle S \rangle$ by using the same technique :

$$L \langle S \rangle = \int_0^L S dx \quad (7)$$

This equation is rewritten by using P_c as the variable instead of x (using Equ. 3):

$$\langle S \rangle = \frac{KA}{L\mu_2 q_2} \int_{P_c(L)}^{P_e} S(P_c) K_{r_2}(P_c) dP_c \quad (8)$$

and by differentiating with respect to the entrance pressure P_e :

$$S(P_e) = \frac{L\mu_2}{KK_{r_2}(P_e)A} \frac{d(\langle S \rangle q_2)}{dP_e} \quad (9)$$

We have simplified this equation by differentiating the product and replacing K_r by its value (Equ. 5):

$$S(P_e) = \langle S \rangle + q_2 \frac{d \langle S \rangle}{dq_2} \quad (10)$$

For each flow rate, the entrance saturation $S(P_e)$, together with entrance pressure P_e gives a point on the P_c curve (since the pressure in water is taken as reference, $P_e = P_c$).

For Ramakrishnan and Capiello, the method was applicable mainly for relative permeability, since the average saturation is too difficult to measure experimentally. In this paper we will show that the capillary pressure curve can also be measured. We will describe the application of the method during primary drainage for a simulated case and for a real experiment with saturation measurement using a CAT scanner.

Numerical example

In order to illustrate the method a numerical primary drainage was run with a given capillary pressure curve (Fig. 3) and relative permeability curves (Fig. 4). Fluid and rock properties are shown in Table 1. The average saturation $\langle S \rangle$ and the entrance pressure are

computed for 9 different oil flow rates by using a one-dimensional numerical simulator (Fisole) developed at IFP (Chardaire *et al.*, 1990).

The values of relative permeability and entrance saturation for the various flow rates are calculated by using Equations 6 and 10. The derivatives are calculated by using the difference between two adjacent points, without any smoothing.

Table 1 Fluid and rock properties for the simulated and the real experiment (SI units)

Rock samples		numerical example	experimental example
	porosity	0.237	0.237
	diameter	0.04	0.04
	length	0.098	0.098
	permeability	$0.390 \cdot 10^{-12}$	$0.162 \cdot 10^{-12}$
Oil	viscosity	$1.3 \cdot 10^{-3}$	$1.3 \cdot 10^{-3}$
Water	viscosity	$1 \cdot 10^{-3}$	$1 \cdot 10^{-3}$

For capillary pressure, the situation is similar to the centrifuge method. We are calculating the entrance saturation which is smaller than the average. However, for the semidynamic method, the calculation is local; i.e., the entrance saturation can be calculated from the average saturation and the derivative at this point (Equ. 10). For the centrifuge method, the local saturation must be calculated from an integral over the whole sample.

For the simulated experiment, there is a good fit between input and calculated data (Fig. 3 and 4). The quality of the fit is mainly controlled by the number of simulated flow rates and the method used for the numerical calculation of the derivatives.

Table 2. Input and calculated data for the determination of the capillary pressure curve

Rate (cc/h)	entrance pressure Pe (mbar)		average saturation <S>	
	Simulated	Scanner	Simulated	Scanner
1	193		0.698	
2	212		0.650	
5	247	140	0.579	0.6
10	286		0.518	
20	341		0.449	
25		185		0.45
50	456	220	0.377	0.38
100	600	294	0.314	0.32
200	833	395	0.255	0.28
300		504		0.27
400		606		0.265
500	1 493	708	0.211	0.26

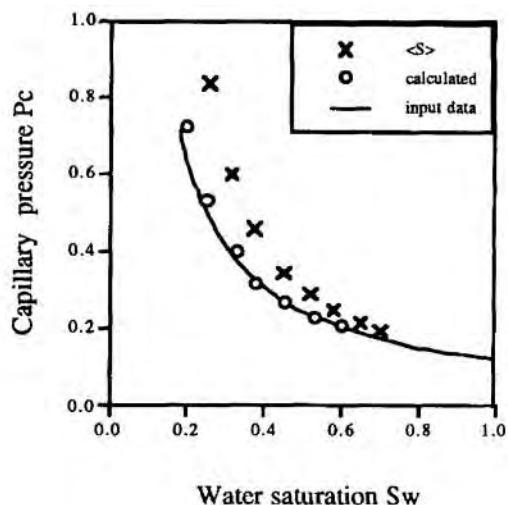


Fig. 3. Numerical example. Input, average and calculated Pc curves

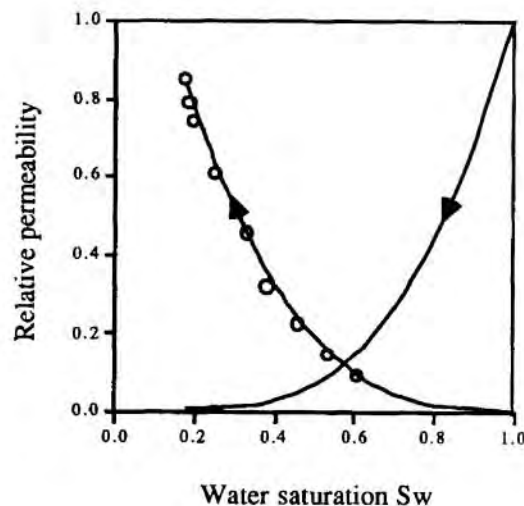


Fig. 4. Numerical example. Input Kr curves (solid lines) and calculated oil relative permeability

Experimental example

The displacements were performed under CAT scanning for saturation measurement to compare measured and calculated local saturations. The average saturations are calculated by integrating the scanner saturation profiles (Table 2). The sample is a Vosges sandstone coated with epoxy resin. The fluid and rock properties are the same as for the simulated case, except for the single-phase permeability (Table 1). Eight oil flow rates were imposed from 5 up to 500 cm³/h. Saturations were measured at 7 locations (Fig. 5) and pressures at 6 locations (Fig. 6). The "washing" water flow rate was 20 cm³/h.

We will first determine the "experimental" and "calculated" capillary pressure curve, then the experimental and calculated oil relative permeability. Finally we will use the calculated Kr and Pc curves as input for numerical flow simulations to compute the saturation profiles which will be compared to the measured profiles.

Capillary pressures

First, the "reference" experimental capillary pressure was determined from the local saturations (linearly interpolated) and the measured local oil pressures for the eight flow rates (Fig. 7). There is a small scatter of the values due to local heterogeneities and experimental uncertainties. The value of Swi is 0.19. The eight values below the main curve correspond to the pressure tap close to the outlet. This effect has not been observed for experiments performed in a Hassler cell. It may be due to a fissure in the epoxy coating, which could create a connection between the pressure tap and the outlet.

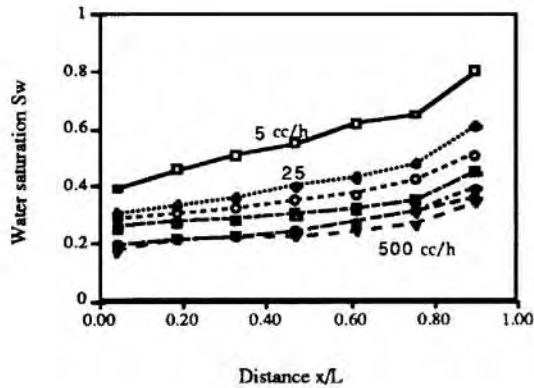


Fig. 5. Experimental saturation profile measured with the CAT scanner for various flow rates (5 to 500 cm^3/h)

The entrance saturation S was calculated from the average saturation $\langle S \rangle$ by using Equation 10 (Table 2 and Fig. 8, (x)). The calculated saturations (open circles, Fig. 8) are close to the experimental values below 400 mbar. For higher pressures, S increases toward $\langle S \rangle$. This nonphysical behavior can be explained by the lack of accuracy for $\langle S \rangle$. The second term of the equation becomes negligible and the entrance saturation tends to the average value. We have discarded these points and taken the extrapolated solid line (Fig. 8) as the calculated Pc curve. The S_{wi} value is 0.20.

Oil relative permeability

The oil relative permeability calculated by using the entrance pressure (Equ. 6) is noisy and cannot be used directly for simulation. A smooth curve is estimated and adjusted by fitting the average saturations $\langle S \rangle$. This estimated K_r (solid line in Fig. 9) agrees with the direct measurements using the pressure and local saturation (Equ. 2). The error bar on the x axis corresponds to the variation of saturation along the sample (Fig. 5), with a constant relative permeability (linear pressure drop, Fig. 6).

Saturation profiles

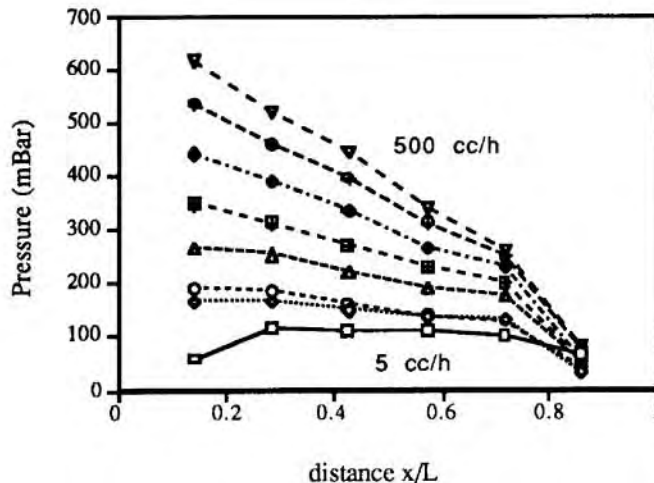


Fig. 6. Experimental pressure profile

The saturation profiles were then calculated for the various oil flow rates by using the numerical simulator with the *calculated* Pc and $K_r(\text{oil})$. The steady state is independent of water permeability and $K_{rw}=(1-S)$ is taken (water is not flowing).

The saturation profiles for the various flow rates are plotted in figure 10. For low flow rates, the simulated and experimental entrance saturations differ (Fig. 5 and 10). This difference is due to the flat shape of the Pc curve. Any small uncertainty about pressure causes a large variation in saturation.

Figure 11 compares for a $400 \text{ cm}^3/\text{h}$ flow rate the saturation measured along the sample (open circle) and the results of two simulations: 1) by using the *calculated* P_c and K_r and 2) by using the *experimental* P_c and K_r . The results are close. However the curvature of the saturation profile is larger than for the experimental profile near the outlet. This difference seems to be related to the capillary end effect. The problem may be due to the uncertainty in extrapolating the saturation profile measured with the scanner (there is no measurement near the outlet). The validity of the outlet boundary condition ($P_c=0$) will also be addressed in further studies.

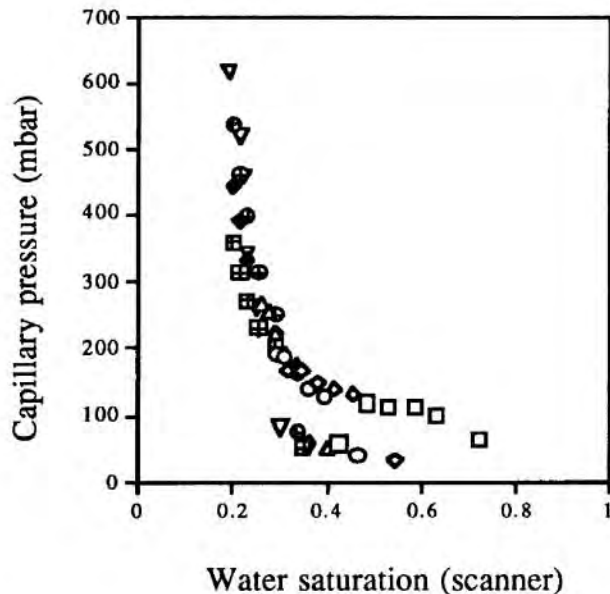


Fig. 7. Experimental drainage capillary pressure curve.

determine P_c and K_r by using the whole series of displacements at various flow rates.

However, the analytical method depends on the accuracy of the differentiation of the measured data. Different techniques have been tested for smoothing and differentiating the data, but without any improvement. The only solution is to improve the accuracy of the measurements, especially for the average saturation near S_{wi} . For the experimental example, the average saturation calculated with 7 local scanner measurements was not accurate enough. Our further experiments will be improved with electrical measurements for the effluent volumes, new design for the end pieces, etc..

The need for local pressure measurements is questionable. In our experiments, the local pressure gradient was useful for the oil K_r determination. Further studies, with more accurate data would answer this question.

The determination of K_r and P_c from our experiments is a nonstandard "inverse" problem. Many studies has been devoted to developing an automatic fitting procedure for

Discussion

The semidynamic method is based on the assumption that the P_c and K_r curves do not depend on the type of flow. Brown (1951) had shown that the P_c curves obtained by a dynamic method (both fluids were flowing) and the porous plate where similar. There is no proof that the relative permeabilities obtained by our method and a steady or unsteady-state method are the same. However, the same problem exists for other methods based on a transient during porous plate or centrifuge P_c measurement.

For the mathematical calculation, there is no doubt about the validity of the method proposed by Ramakrishnan. The main advantage of this method is to

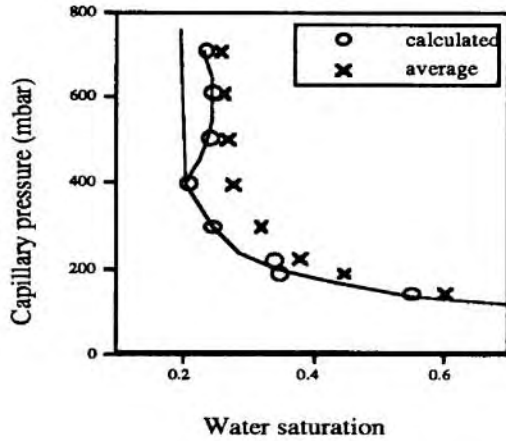


Fig. 8. Average (x) and calculated capillary pressure (o).

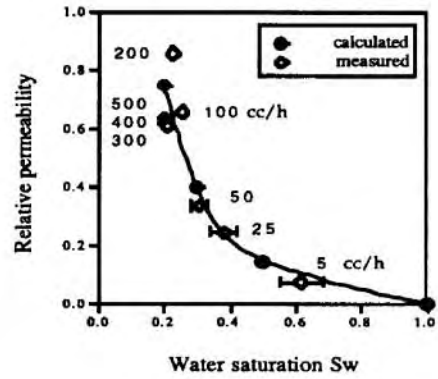


Fig. 9. Calculated (solid line) and experimental oil relative permeability.

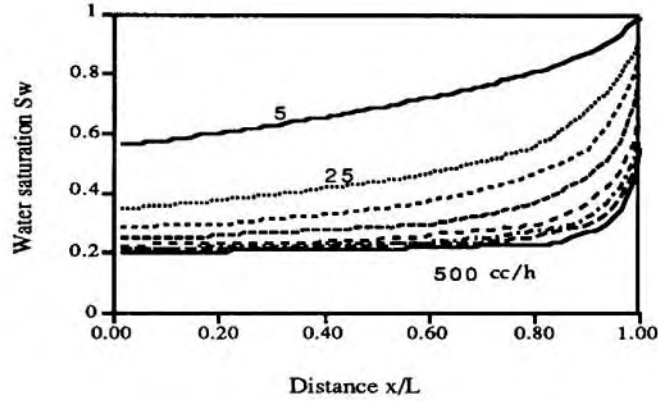


Fig. 10. Computed saturation profiles.

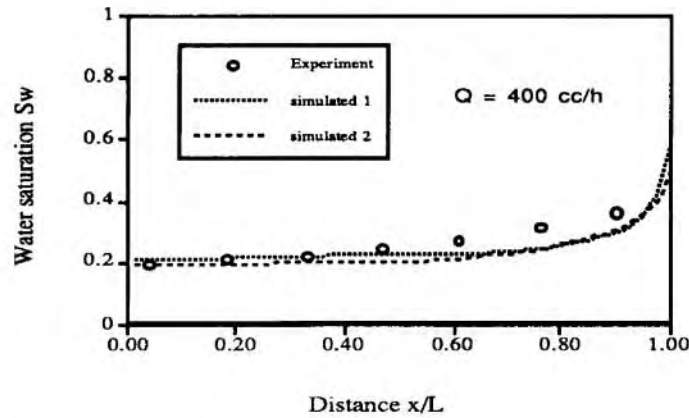


Fig. 11. Comparison of experimental and calculated saturation profiles.

a single nonsteady state displacement (Chardaire et al., 1990, Richmond and Watson, 1990). A similar approach could be developed for the semidynamic method.

Conclusion

The semidynamic method provides the entire water-oil capillary pressure cycle (drainage and imbibition for both positive and negative P_c), for any type of wettability. It is based on the steady-state injection of one fluid through the sample. In order to simplify the method, the measurement of the local saturation has been replaced by its calculation from the average saturation, as in the centrifuge method. In order to check this calculation, several experiments were performed with both measurement (CAT scanner) and calculation of the local saturation.

The analytical calculation of the local saturation proposed by Ramakrishnan and Capiello (1991) uses the entrance pressure and average saturation. It agrees with scanner measurements for intermediate values of saturations, but there is no accuracy of the S_{wi} value. The reason is that the calculation is based on the derivative curve of the pressure vs. flow rate.

Results of the analytical method are then used as a first guess for numerical simulations of the displacement. The final P_c and K_r curves are then determined by fitting the simulated average saturation and local pressure with the experimental values. The whole range of saturations, and especially S_{wi} is then accurately determined within the accuracy of saturation measurement from CAT scanning (± 2 saturation units).

Nomenclature

A	cross-section area of the sample	q	volume flow rate
K	single-phase permeability	S	Saturation
K_r	relative permeability	$\langle S \rangle$	average saturation
L	length of the sample	x	distance from the entrance
P_c	capillary pressure	μ	viscosity
P_e	entrance pressure	indices o, w	oil, water
		indices 1,2	in situ and injected fluid

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